A Petri Net-based Life Cycle Cost Analysis Approach

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Railway infrastructure providers, such as Network Rail, who owns and manages the British railway infrastructure, can improve the performance and reduce the life cycle cost of their assets through delivering effective asset management. Having the capability to use computer based models to predict the future performance and life cycle cost of an asset group is a key enabling mechanism for implementing effective asset management. Decision makers can determine the optimum maintenance strategy and the best allocation of capital expenditure based on evidence from modelling results. This paper shows how probabilistic modelling can be used to evaluate asset management projects of the railway overhead line equipment (OLE) system and undertake a life cycle cost analysis through the use of a stochastically timed High Level Petri Net. A complete modelling framework has been developed, where the components and their maintenance strategies are selected as inputs, and the Petri Net model is used to calculate outputs associated with the performance and life cycle cost of the OLE system for the corresponding components and strategies considered. This paper presents the practical use of the developed model and describes how the outputs can be used by asset managers to understand the expected system performance and cost over its life cycle. The range of outputs described are the most detailed for such models studying the OLE and other engineering systems in literature. Whilst the railway OLE system is used as an example study, the modelling framework is transferable to asset management projects for other engineering systems.

1 Introduction

Overhead Line Equipment (OLE) is a part of the 25kV alternating current overhead electrification system, the preferred railway electrification system in Britain, which currently represents 63% of the

5000 kilometres of electrified railway network[1]. With such a large electrified network and many electrification schemes planned in the near future, Network Rail (the British railway infrastructure provider) can achieve substantial economic savings through specifying the OLE installation types and maintenance regimes that meet the required outputs at the lowest life cycle cost. If life cycle cost analysis can take account of the main processes that influence the cost and performance of an asset group (namely asset degradation, failure, inspection and maintenance) over the entire life cycle of the system, asset management and investment decisions can be better informed and based on evidence from modelling results.

The term asset management refers to the processes implemented by an organisation to realise value, which can be related to performance or be purely monetary, from their assets[2]. As part of its asset management strategy, Network Rail aims to maintain its current portfolio of railway assets and correctly specify the assets to be installed in new systems, so that the required outputs, such as system reliability and the permissible railway line speed, can be achieved at the lowest life cycle cost for the system[3]. The life cycle cost of an asset is composed of its acquisition costs, associated with its design and installation, and its ownership costs, associated with its failure and maintenance over the asset's lifetime[4]. Life cycle cost analysis can be undertaken to calculate the total cost of asset ownership, by quantifying all the significant expenditures that are required throughout the entire life cycle of an asset. Different asset selection and maintenance strategies can be examined during the life cycle cost analysis, in order to find the most suitable asset management strategy, where the best value is obtained from the assets[5]. Therefore, rather than implementing strategies based on the lowest initial cost in the short term, the entire life cycle of an asset should be taken into account. For example, Network Rail generally considers different asset types (such as the railway track, structures, OLE, etc.) separately, since different modelling methodologies may be better suited for different asset types and separate teams are responsible for their asset management. However, the results are collated to obtain the expected life cycle cost for a group of assets on a part of the network. A 100-year period of asset operation is commonly chosen for the analysis, which is used for making decisions at the strategic level, since within this timeframe most of the assets in a railway system will have exhibited their entire life cycle. At the same time, the expected costs in the short to medium term (from 5 to 30 years) are also obtained to support more immediate projects.

The principle of life cycle cost analysis was developed in the 1960s by the US Department of Defence and has since been used in other sectors, notably the construction industry, although a widespread embracement of considering all the costs incurred over the lifetime of an asset has been slow in other industries[6]. The assets that are most suitable to life cycle cost analysis commonly have high ownership costs (for example, due to large maintenance costs) relative to the acquisition costs (associated with the initial investment), and they can be modified in terms of both individual component design and maintenance strategies[7]. Over 50 published case studies were reviewed[6] describing life cycle cost analysis studies in a number of industrial sectors. For a detailed life cycle cost analysis, which takes into account the uncertainty associated with the processes considered, the authors state that stochastic methods should be used for calculating the life cycle cost of a system. Around 50% of the studies reviewed used stochastic methods, as it is often difficult to obtain detailed data and information required to develop a stochastic model, and fixed deterministic values can be more easily obtained from cost information and engineering judgement. However, stochastic methods for life cycle cost analysis are becoming more popular and have been developed for a number of different types of assets, such as bridges[8], roads[9], wind farms[10], offshore platforms[11] and water supply systems[12]. In the case of the OLE assets, there is a large amount of uncertainty associated with the degradation and failure of the components throughout their operational life. As a result, stochastic methods are required to accurately model the degradation and failure events of the OLE, in order to calculate the expected maintenance and failure costs of the system over its life cycle. The data and information required for a stochastic model can be obtained through close collaboration with the owners of the assets, such as Network Rail in this study.

There has been a limited amount of research in literature to date, focusing on modelling the life cycle cost and asset management of the OLE. Some stochastic models have been developed to estimate the life cycle cost of the OLE components and evaluate system reliability[13,14,15]. Such models usually consider fixed-time interval preventative maintenance and corrective maintenance after a component failure, and do not take account of condition-based maintenance strategies. The latter strategies are currently implemented by Network Rail, whereby an OLE component's maintenance is scheduled based on the condition revealed during routine inspections, rather than fixed-interval time based maintenance. In addition, due to the large number of components on the OLE system and costly closures of the track due to maintenance, a strategy of grouping of maintenance works is needed, where a number of components are maintained opportunistically (i.e. earlier than planned) resulting in a reduced life cycle cost. Since a more sophisticated modelling methodology is required to consider such asset management actions accurately, Petri Nets (PNs) have been chosen as the modelling method, due to their suitability to model the reliability and behaviour of engineering systems whilst considering dependencies between individual components of the system and their processes, such as degradation, failure, inspection and maintenance[16,17]. The use of PNs for modelling asset management processes of engineering systems has become more prevalent in recent years. For example, a PN modelled the degradation, inspection and maintenance of a wind turbine to predict the future condition and maintenance requirements for the components and calculate the expected maintenance costs over the life cycle of the system[18]. The work described in this paper is based on a High Level Petri Net (HLPN) model that is used to simulate the degradation, failure, inspection and maintenance of the OLE components[19,20]. HLPNs add further functionality to standard PNs, thus enabling complex processes to be modelled (such as condition-based maintenance and opportunistic maintenance) in a more efficient and intuitive manner, through allowing the tokens in the PN to contain additional information that can be manipulated by functions within the transitions and their arcs[21].

The novelty of this paper lies in developing a probabilistic asset management and life cycle cost analysis framework, which has not been proposed at this level of detail for the railway OLE system before. The method is based on a whole-system approach, where the relationships between the individual components of the system are considered, in terms of their degradation, failure, inspection and maintenance processes, which introduce further complexity to the model and also give a realistic representation of the factors that need to be considered while making decisions on asset management projects. In addition, a life cycle cost analysis tool is developed, which can be used by project managers to inform their decisions for the allocation of expenditure, considering the trade-offs between the predicted cost and performance for component types and the overall OLE system.

This paper gives an overview of the proposed framework and focusses on the outputs of the stochastic HLPN model, used to calculate statistics associated with the cost and performance of the OLE system over its life cycle. A brief description of the main features of the model (Section 2) and its use as a tool to study the asset management and life cycle cost of the OLE is provided (Section 3), followed by the presentation of the main outputs obtained from an example study analysis (Section 4). A discussion of how each output can be used by decision makers to study the performance of the components and how maintenance strategies can be evaluated over the entire life cycle is also presented.

2 Proposed Framework and Life Cycle Cost Analysis Tool

2.1 OLE system description

The OLE refers to the conducting wires, insulators and supporting components that provide electric trains with their traction power along the length of an electrified line. Since the OLE system has no redundancy, individual OLE component failures often result in failure of the system, which can lead to delays of the timetabled train service. The main OLE components are shown in Figure 1 and they repeat down the entirety of an electrified line. To obtain its traction power, a train's pantograph makes a physical and electrical connection with the contact wire, which is suspended below the catenary wire (by droppers) and held in position by registration equipment that is attached to structures that raise the OLE above the track[22].

Figure 1 Main OLE Components

2.2 Proposed framework

A HLPN model has been developed in this study to represent the main processes associated with the asset management and life cycle cost of the OLE system. The main processes considered are the degradation, failure, inspection and maintenance of the components. The occurrence of these processes over a 100-year time period is modelled individually for each instance of each component type in the section of OLE studied. The components studied in detail are the catenary wire, contact wire, droppers, insulators, registration equipment, return conductor, and structures, as shown in Figure 1. These components were chosen because they are present in every section of OLE, and their reliability and maintenance requirements have a significant impact on the cost of the system over its life cycle. Further details of the HLPN developed can be found in other work by the authors[19,20].

The original concept of the Petri Net was developed by Carl Petri[23]. A Petri Net, where a HLPN is an advanced version of PNs, is a directed graph with two types of nodes, called places (denoted by circles) and transitions (denoted by rectangles), which are linked by directional arcs. It provides a graphical representation (see Figure 2) of dynamic processes in a discrete event simulation framework, for example, an asset moves from a working state (P1) to a failed state (P2).

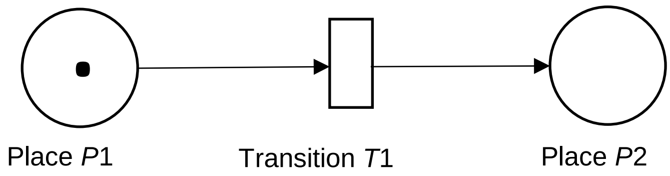

Figure 2. Petri Net Example

A place is used to represent a state or condition of the asset and it can be marked with a token (or several tokens), which means that the asset resides in a particular condition. The tokens are removed from one place and put into another place using transitions, also known as transition firing, which mimics the change of the state, for example, an asset which was working becomes failed. The move of tokens is possible if the transition, such as $T1$, is enabled, i.e. when all input places to the transition have the amount of tokens that is equal to the multiplicity, also known as weight, of the arc. Usually the multiplicity is one, as in Figure 2, but a higher multiplicity can also be considered. Once the transition is enabled, a delay time to fire is randomly generated, using a probability distribution, for example, obtained from the analysis of failure data of the asset. Once the delay time runs out, the transition is fired. The delay time can also be constant or instant, i.e. equal to 0.The HLPN model is evaluated using Monte Carlo simulation and various statistics are collected by recording the number of times a token enters a certain place along with the time of entry.

Figure 3 shows a hierarchical PN that represents the whole system model. There are separate subnets for the component types that are studied in detail, where the degradation, failure, inspection and maintenance processes are modelled by moving tokens that represent a component between places, such as a place for the good condition and a place for the degraded condition of the component. Each subnet is represented as a super transition, denoted by double lined squares. These subnets can be viewed as functions and the places that are connected to them (by arcs that connect to transitions within the subnets) are input or output events of the processes modelled within the subnets. Failures due to external influences, such as system failures that were not caused by the OLE components studied in detail, e.g. bird strikes causing the circuit to trip, and the renewal of the catenary and contact wires are also modelled in separate subnets. Other places in Figure 3 are used to keep track of maintenance activities in an access area, a wire run or a span, and collect statistics of the outputs. Further details of the examples of the subnets can be found in other work by the authors[19,20].

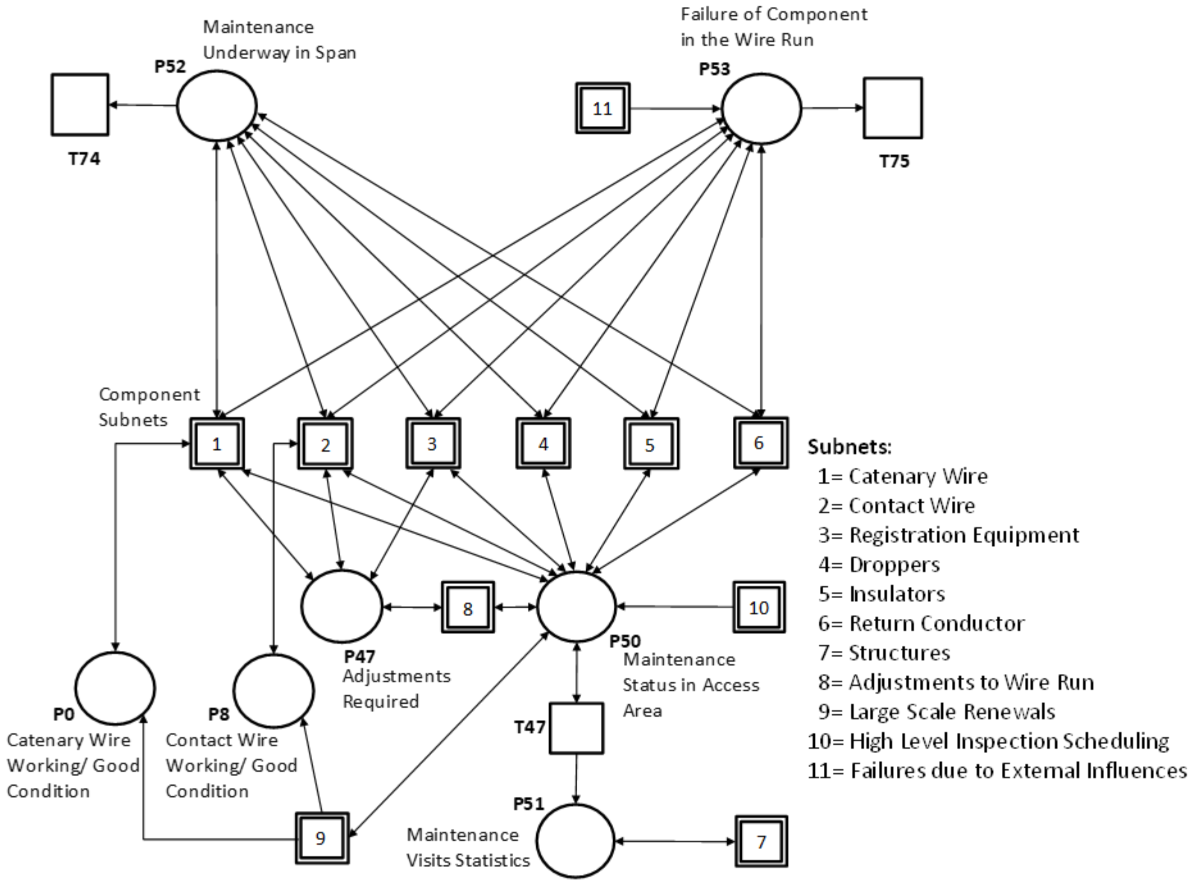

Figure 3 Overview of the High Level Petri Net Model

Note that the proposed framework can be easily adapted to other engineering systems that undergo the processes of degradation, failure, inspection and maintenance.

2.3 Asset Management and Life Cycle Cost Analysis Tool

The use of the HLPN model in asset management and life cycle cost analysis is illustrated in Figure 4. The HLPN is constructed in Excel with the place and transition information written in spreadsheets, and a graphical depiction of the model also provided. The number of tokens, that represent the different components studied in a particular part of the network, can change dynamically, as can the frequency of different intervention actions, such as the inspection interval or the component maintenance scheduling times. These are listed as user inputs because when the HLPN model is used, the user specifies the components in the area studied, e.g. the number of components of each type, their corresponding degradation and failure behaviour, and the intervention strategy considered. The macros in Excel then generate the number of tokens, transition firing times and place marking in the HLPN according to user inputs.

The text files are then generated for the current configuration of the HLPN, and these are read into bespoke C++ software that has been developed to generate the model then evaluate it using Monte Carlo simulation. Various events are recorded for each simulation and once the mean total yearly cost has converged for each year studied (such that it does not change more than 0.1% with further simulations) the Monte Carlo simulation is completed and the outputs are calculated from the recorded statistics.

The model outputs are obtained at several levels of granularity, for example, for each component type and for the system as a whole, for an individual wire run and for the entire section of OLE studied. Note that a wire run relates to the contact and catenary wires, which are approximately one mile long. Such outputs contain statistics that refer to the number and cost of component and system maintenance works and failure events.

The complete analysis tool, shown in Figure 4, demonstrates how the model can be used for evaluating OLE asset management projects and analysing life cycle cost, where component information and the controllable asset management decisions, defined as the intervention strategy, are provided as inputs to the model. During the analysis, the outputs that describe the impact of the asset management decisions, in terms of the performance and cost of the components and the system, are obtained. The tool is aimed at decision makers who need to know the expected life cycle cost of a system. However, short and medium term analysis of the expected costs and performance of a system can also take place using this tool.

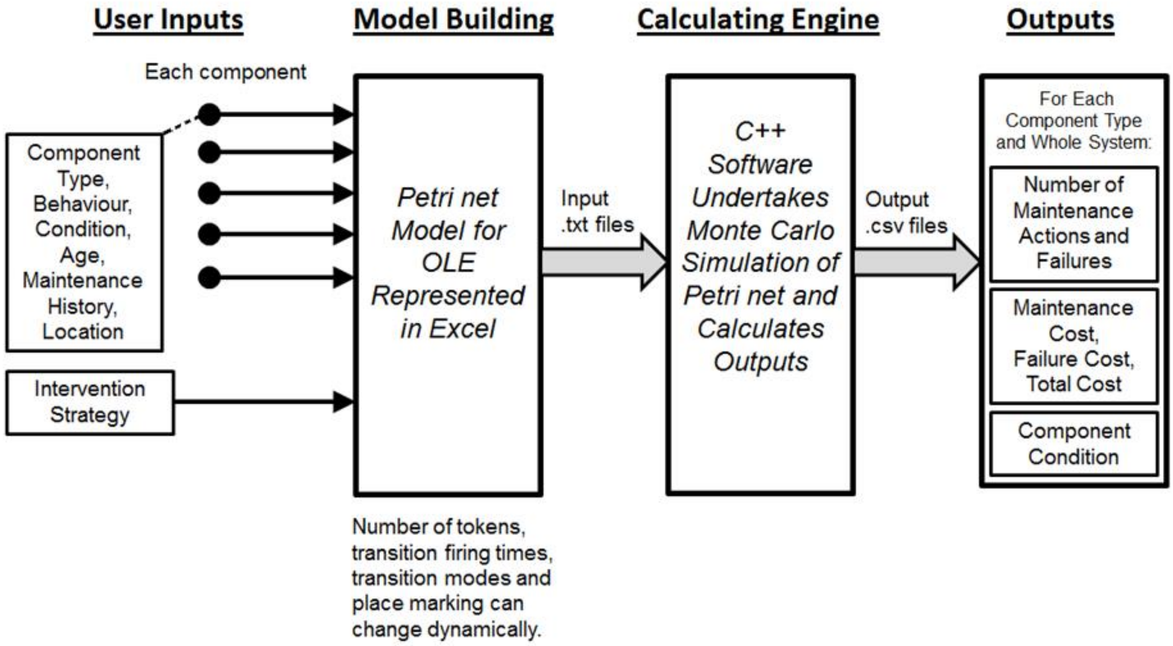

Figure 4 Overall OLE Asset Management and Life Cycle Cost Analysis Tool

3. Model Outputs

In the example study presented in this paper, the HLPN model was used to simulate 100 years of operation for all the main OLE components in one maintenance access area, these components are shown in Figure 1 and in the overview of the model in Figure 3. An access area is defined as two miles of the electrified railway line, where the components can be maintained during the same maintenance visit. In this access area, there were two wire runs of the OLE studied which represent approximately 2 miles of the line. A span is defined as the distance between each set of structures which is approximately 60m. For the 52 spans studied, one instance of each type of the OLE components was considered. Note that there are 2 insulators on each structure, therefore 104 insulators were studied in the model.

The asset management intervention strategies that are considered in this example study replicate the strategies, currently implemented by Network Rail for a high category line[24]. Three types of inspection are considered in the model: cab patrol inspection occurs every 14 days, low level walking inspection occurs every 28 days and high level intrusive inspection (where maintenance can also be undertaken) - every 4 years. For illustration purposes, the inputs for the catenary wire model are given in Table 1, including the degradation and failure rates and maintenance and inspection frequencies. The distributions and their parameters were estimated using literature on OLE component degradation behaviour[22], NR data analysis and discussions with NR maintenance engineers.

Table 1 Model Input Values for the Catenary Wire

Transition time	Parameter
From Good State to Degraded State	Weibull Distribution (WB): β = 2.5, η = 43800 days
From Degraded State to Severely Degraded State	WB: β = 3, η = 1825 days
From Good State to Failed State	Exponential Distribution (ED): λ = 5.07E-07 failures per day
From Degraded State to Failed State	ED: λ = 2.74E-04 failures per day
From Severely Degraded State to Failed State	WD: β = 3, η = 500 days
Maintenance Time when in Degraded State	Within 180 days
Maintenance Time when in Severely Degraded State	Within 7 days
Low Level Inspection to Reveal Degradation	Every 28 days

The outputs obtained using the proposed HLPN model are detailed in this section: the number of maintenance works and their cost, the number of failures and their cost, and the change in the component condition over time using a chosen maintenance strategy. These outputs are obtained for each component type on the access area of OLE studied. Outputs of the life cycle cost analysis are also calculated at the system level, such as the maintenance cost, failure cost and the total cost (the combination of failure and maintenance costs) for the access area. Maintenance cost consists of the cost of accessing the line to undertake maintenance or regular inspections in addition to the actual component repair or replacement costs. Failure cost consists of delay and non-delay cost, where the delay cost is incurred in the form of a fine that Network Rail pays to the train operating companies due to the failure and is proportional to the number of delay minutes. The delay cost normally outweighs the non-delay cost by far, which represents the cost of the repair work after the failure. Note that at the request of Network Rail, in this paper the outputs indicating a cost value have been multiplied by a factor to hide the true costs.

The outputs are annualised to provide yearly summaries of the statistics, associated with each component type and the overall system, in order to analyse the change in values over the life cycle. These outputs are expressed as both yearly values and cumulative yearly values, providing a comprehensive set of statistics that describe the expected behaviour and cost of the different component types and the overall system. This feature enables the calculation of the total cost in any year, rather than for the whole 100 year period demonstrated here. Note that in addition to the mean values that are shown in the following figures, other statistics that help to quantify the uncertainty associated with the behaviour of the system, are obtained (such as the maximum, minimum and upper and lower quartiles). These statistics are presented later in Table 2.

When undertaking life cycle cost analysis, it is common to discount the future costs and calculate the net present value by taking into account the time value of money and the fact that people prefer to receive income and services sooner and defer costs for the future. The costs presented in this paper are not discounted to enable the reader to view the change in the cost values over time without interference from the discount rates. When necessary, the results can be multiplied by the discount factor to study net present value costs.

The model outputs were validated by comparing the number of maintenance actions, failures and life cycle cost to the values calculated in the life cycle cost model developed by Network Rail and the values revealed through analysis of historical data. Additionally, as described in the following sections, the results obtained and the change in values over the system's life cycle are easily explicable and expected under the maintenance strategy studied.

3.1 Maintenance Works Related Outputs

The expected number of maintenance actions and the maintenance cost are calculated for each year in the 100-year period modelled. These outputs allow the behaviour of the different component types and of the system to be analysed, demonstrating how the maintenance requirements change over the life cycle of the system and when more investment is needed to preserve the condition of the asset. Such information can allow asset managers to predict the resources, such as the number of staff or spare parts that are required to keep the system in the operating condition. For example, Figure 5 shows the mean yearly number of scheduled maintenance works for the catenary wire, and the overall number of scheduled maintenance visits for the access area. It can be seen that the mean yearly number of maintenance actions increases as the components age. The increased number of maintenance visits required during the first two years of the operation is due to early component issues, caused by installation errors. After year 70, a renewal of the contact and catenary wires is scheduled, which returns the catenary wire to a new condition, where it is less likely to require maintenance. Since maintenance of other OLE components is also scheduled to take place at the same time as the renewal (through applying opportunistic maintenance), there are fewer maintenance visits occurring that year. Note that the spike every four years for the number of maintenance visits to the access area coincides with the frequency of high level intrusive inspections, where the maintenance of some degraded components will take place at the same time, until the line has to be reopened for usage. There are fewer maintenance visits in the year following the high level inspection, because the system is in a better condition and maintenance is less likely to be required. Overall, this output gives some detailed information about the expected maintenance volumes each year.

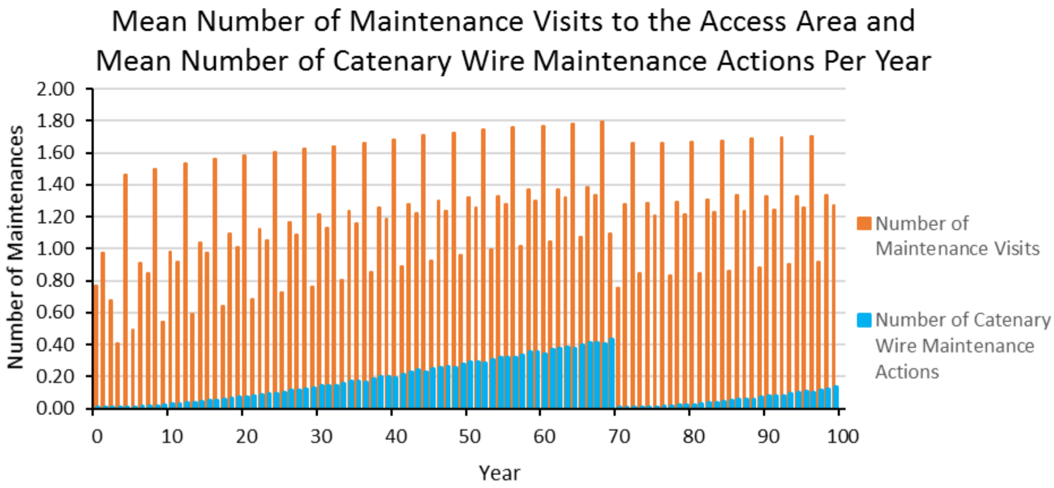

Figure 5 Mean Number of Maintenance Visits to the Access Area and Mean Number of Catenary Wire Maintenance Actions Per Year (With Opportunistic Maintenance)

Outputs describing the cumulative number of maintenance actions and the cumulative maintenance cost can also be calculated. Such outputs provide an overall summary of the expected maintenance volumes and their associated costs over a certain period.

3.2 Failure Related Outputs

The outputs related to component and system failures are similar to the maintenance outputs, shown previously in Section 3.1. Such results can be used by asset managers to predict and compare the behaviour of different components, in terms of the expected number of failures and failure costs, over their life cycles. For example, Figure 6 shows the mean yearly number of failures and the mean failure cost for the catenary wire. It can be seen that the number of failures follows a similar trend to the number of catenary wire maintenance works, as shown in Figure 5. As the catenary wire becomes degraded over time, its probability of failure increases. The fluctuation is due to the scheduling of the high level intrusive inspections, where the catenary wire is likely to be maintained if it is degraded, thus lowering the probability of failure in the years when the inspection occurs.

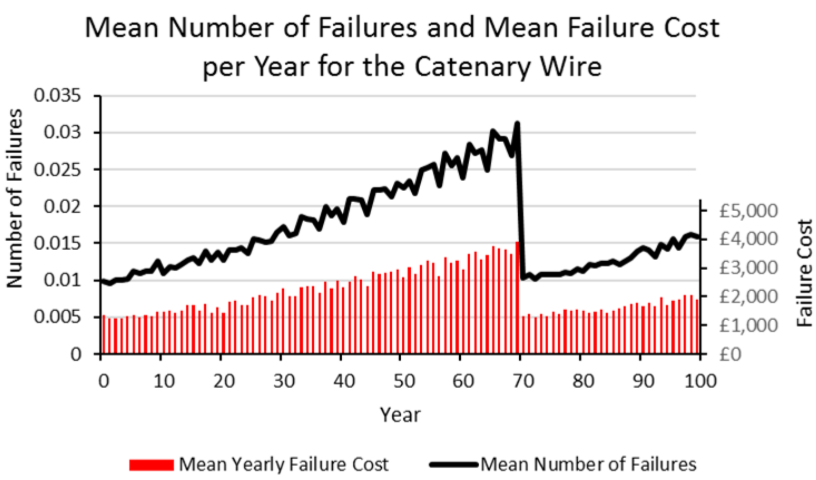

Figure 6 Mean Number of Failures and Mean Failure Cost per Year for the Catenary Wire

Figure 7 shows the mean number of cumulative failures for the different component types. Note that external influences in the figure refer to failure events that are attributable to the OLE, but are not caused by the failure of any of the OLE components and there is no damage to the components. Examples of external influences include bird strikes or encroaching vegetation causing the power supply to trip, or objects being caught in the OLE and trains having to stop until the objects are removed. These failures occur randomly and with a far greater rate than the failure of any of the OLE components due to degradation and lack of maintenance. However, since external failures are relatively simple to rectify, they do not generally result in a significant disruption to the service, therefore, the cost of such failures is low, in comparison to the OLE component failures. For example, Figure 8 shows the cumulative failure costs for the different OLE component types. The cumulative failure cost of the contact wire is significantly higher than that of the other components, because the cost associated with its failure is very high, due to an increased risk of extensive damage if the contact wire splits. The cumulative number of failures for droppers and insulators is only slightly smaller than that of the contact wire, but these failures are less likely to result in severe disruption to the timetabled service, therefore, their cumulative failure cost is relatively low. On the contrary, despite the relatively low occurrence of catenary wire failures, a failure of this component is more likely to result in a large disruption to service and, therefore, the cumulative failure cost for the catenary wire is large. These results suggest that particular attention should be placed on preventing contact and catenary wire failures.

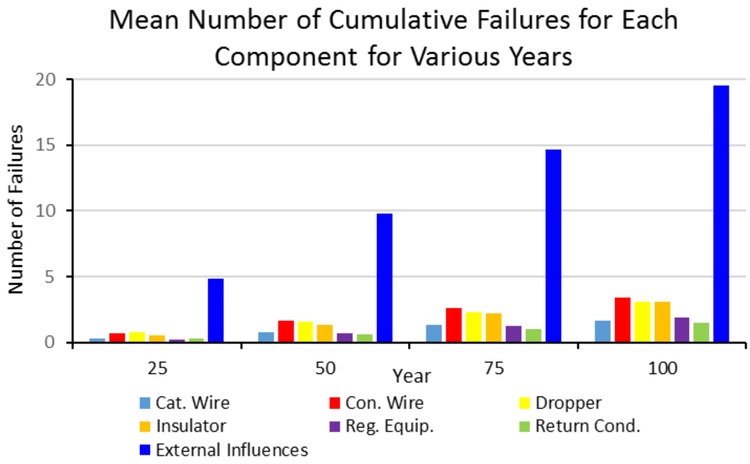

Figure 7 Mean Number of Cumulative Failures for Each Component for Various Years

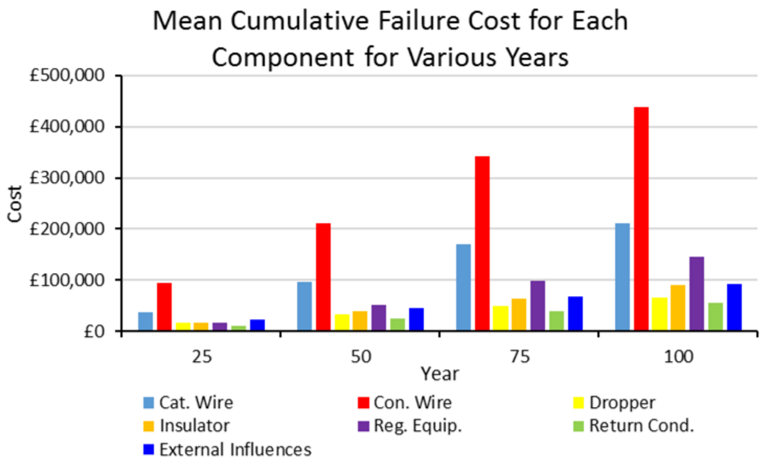

Figure 8 Mean Cumulative Failure Cost for Each Component for Various Years

Predicting how the number of system failures will change over time and understanding the severity of these different failures, in terms of the costs incurred, can be useful for evaluating the expected performance of the system in terms of its reliability. For example, Figure 9 shows the mean total yearly number of failures, split into the 3 categories, according to the failure cost incurred. The different categories are defined as follows: major service affecting failures (failures costing more than £240k and causing substantial delays to the service), moderate service affecting failures (failures costing between £40k and £240k and causing moderate delays) and minor service affecting failures (failures costing less than £40k and causing small delays). It can be seen that the vast majority of failures are minor service affecting failures. The number of major service affecting failures remains low and relatively constant across the entire period analysed. This is expected because these failures are very rare events. The total number of failures is seen to increase from approximately 0.28 failures per year initially, to 0.38 failures per year at year 70. After the renewal in year 71, the number of failures per year lowers to between 0.3 and 0.35 failure per year, and increases only slightly until year 100. Note, as described previously, during the years where a high level intrusive inspection takes place, the failure rate after the inspection is lower because component defects are more likely to be revealed and maintained at the start of these years, thus lowering the number of failures.

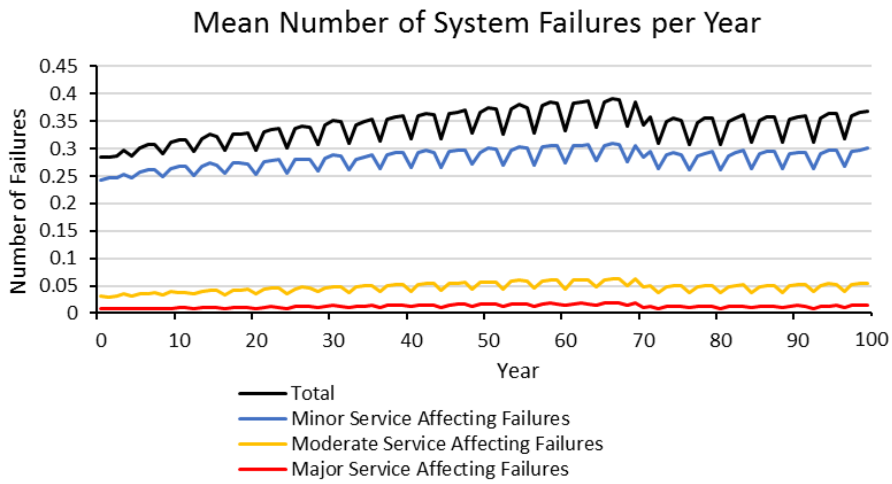

Figure 9 Mean Number of System Failures per Year

3.3 Component Condition Related Outputs

In the HLPN model, the time that a component of a particular type in the wire run spends in each condition band can be obtained, where each condition band refers to a number of degraded components (of the same type) in the wire run. For instance, for the contact wire the first condition band, signifying a good condition, refers to no sections of contact wire being degraded (e.g. being excessively worn), or containing a splice, which through maintenance was put in to rectify previous degradation or failure of that section of the wire. The second condition band, signifying a satisfactory condition, refers to the wire having 1 or 2 degraded or spliced sections. The third condition band, representing a poor condition, refers to the wire having 3 degraded or spliced sections. Finally, the fourth condition band, signifying a very poor condition, refers to the wire having 4 or more degraded or spliced sections. Note that a section of the contact wire containing a splice is still considered degraded (even though the splice rectified the previous level of degradation), because the wire is not in a good condition, and the presence of splices in the wire run can adversely affect the behaviour of the overall catenary system. The mean time spent in each condition band each year can be obtained from the model.

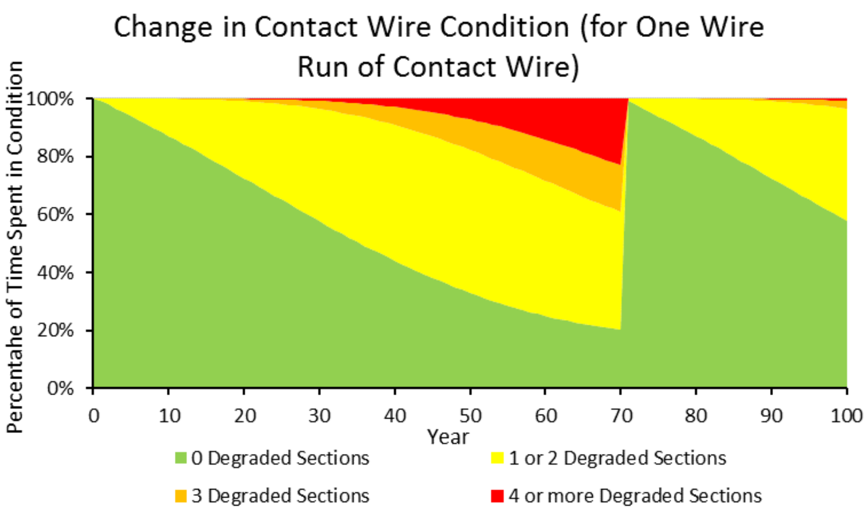

Figure 10 Change in Contact Wire Condition Over Time

For example, Figure 10 shows the change in the condition of the contact wire in one wire run of OLE in the access area in this example study. It can be seen that as the contact wire ages, more sections become degraded or contain a splice. In year 70, the contact wire is renewed, therefore, there are no splices or degraded sections left anywhere in the wire run. Year 70 seems to be a suitable year for renewal, because at this time there is approximately only a 20% chance of the wire containing no degraded sections and the probability of the wire being in a very poor condition, i.e. with 4 or more degraded sections, is over 10%, and it will continue to increase rapidly, if no renewal projects are implemented.

3.4 System Life Cycle Cost Related Outputs

Outputs related to the system life cycle cost give a detailed overview of the different expenditures that are incurred over the life cycle of the system. Decision makers can use such outputs to compare different strategies or project options, and allocate the budget accordingly.

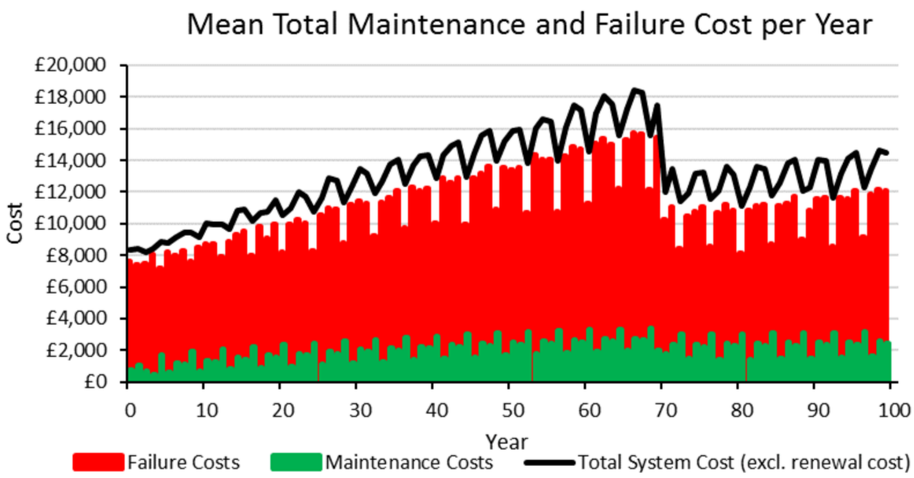

Figure 11 Mean Yearly Total Maintenance and Failure Costs

For example, Figure 11 shows the mean total yearly maintenance cost (excluding the large cost of renewing the catenary and contact wires after 70 years) and the mean total yearly failure cost. The total yearly cost, as a sum of the maintenance and failure cost, is also obtained. It can be seen, that in each year the mean failure cost is significantly greater than the mean maintenance cost. This is due to the large costs incurred because of fines relating to the disruption to the timetabled service during a failure event. The yearly maintenance and failure costs increase over time as the components age, and become more likely to require maintenance or fail. In year 71 the renewal of the contact and catenary wires takes place (along with opportunistic maintenance of other degraded components) which improves the condition of the system, resulting in fewer failures and a lower failure cost in the following years. Note that the fluctuations in the failure cost are due to the occurrence of the high level intrusive inspection every four years. During the years when a high level inspection takes place, the failure costs are lower because component defects are more likely to be identified and maintained before a failure occurs. Also, the maintenance cost peaks during these years, since the high level inspection and additional opportunistic maintenance is undertaken.

Figure 12 shows various statistics describing the cumulative total yearly system cost, i.e. the total cost of the system up to and including a given year. The interquartile range gives an insight into the expected range of costs and shows the associated uncertainty. Due to the failure cost distributions (which were obtained using NR data) being lognormally distributed, in some simulations the failure costs incurred were very large, which resulted in the mean total cost to be positively skewed. As a result, the mean cost is greater than the median cost throughout the 100-year period. Note that the large increase in year 71 is due to the renewal of the catenary and contact wires.

Table 2 lists the values obtained for the cumulative cost statistics at 100 years, and the results for the total cost, and the maintenance and failure costs individually. For comparison, the results are given for policies with and without opportunistic maintenance. Note that the standard deviation and inter quartile range are the same for the total cost and the failure cost, because the corresponding values of these statistics for the maintenance cost is very low. This suggests the uncertainty of the total cost is predominantly due to uncertainty of the expected failure costs. It can be observed that the mean total cumulative cost is calculated to be approximately 20% larger if opportunistic maintenance is not undertaken. This is because opportunistic maintenance results in fewer maintenance visits and the component maintenance actions are undertaken sooner, which also reduces the number of failures. Table 2 illustrates how two maintenance strategies can be compared using the tool, and the choice of the strategy can be evidence by the modelling results.

To make better informed asset management decisions, it is important that the complete range of results is understood and used, so that the uncertainties are accounted for. The cumulative yearly maintenance cost, failure cost and total cost for each simulation were recorded from the model, to allow histograms, which express the number of simulations that contain costs within certain ranges, to be plotted. For example, Figure 13 shows the distribution of the cumulative total system cost for 100 years. There is a large range of costs obtained from the simulations, and a 2% chance of the total cost being greater than £3.6 million. However, approximately 50% of the simulations resulted in a total cost between £1.05 million and £1.8 million. Overall, the distribution of cumulative total costs for different asset management projects can be compared using a number of different outputs, and the level of uncertainty can be also accounted for.

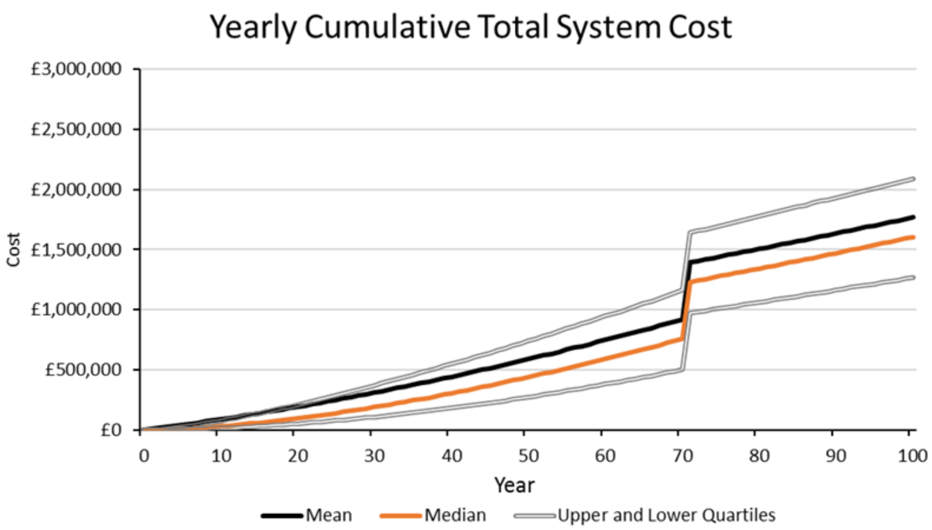

Figure 12 Yearly Cumulative Total Cost

Table 2 Year 100 Cumulative Cost Statistics (With and Without Opportunistic Maintenance)

	Total Cost		**Maintenance Cost (including renewals)**		**Failure Cost**	
	With Opp. Maint.	*Without Opp. Maint.*	*With Opp. Maint.*	*Without Opp. Maint.*	*With Opp. Maint.*	*Without Opp. Maint.*
Mean	£1.770 M	£2.108 M	£0.670 M	£0.798 M	£1.100 M	£1.310 M
Median	£1.606 M	£1.942 M	£0.670 M	£0.798 M	£0.935 M	£1.143 M
Maximum	£7.110 M	£7.839 M	£0.715 M	£0.877 M	£6.447 M	£7.065 M
Minimum	£0.704 M	£0.847 M	£0.628 M	£0.724 M	£0.039 M	£0.071 M
Standard Deviation	£0.689 M	£0.749 M	£0.011 M	£0.017 M	£0.689 M	£0.749 M
Upper Quartile	£2.090 M	£2.477 M	£0.678 M	£0.809 M	£1.419 M	£1.679 M

Lower Quartile	£1.271 M	£1.565 M	£0.663 M	£0.787 M	£0.600 M	£0.766 M
Inter Quartile Range	£0.819 M	£0.913 M	£0.014 M	£0.022 M	£0.819 M	£0.913 M

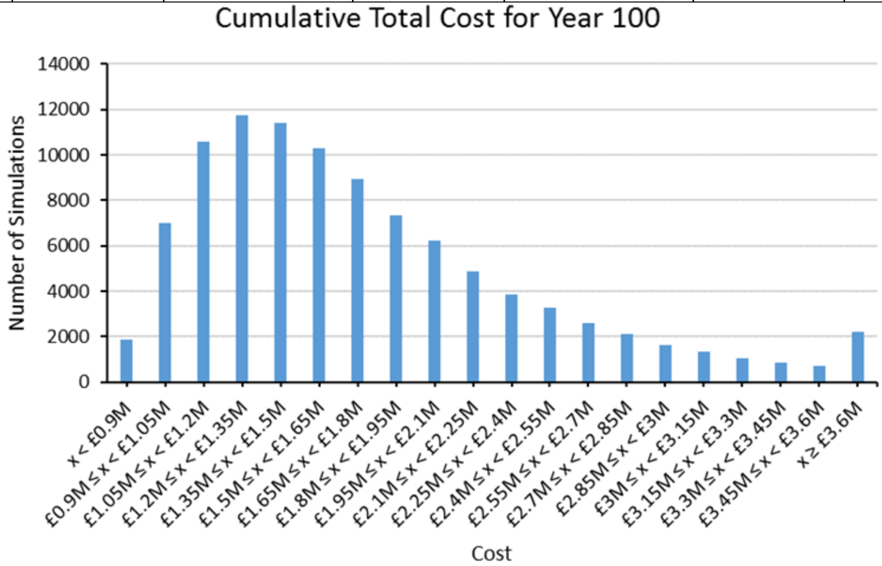

Figure 13 Distribution of the Cumulative Total Cost for 100 Years

Note that as it was the case with the proposed framework, this range of outputs can be obtained for other engineering systems that are of concern when making asset management decisions.

4 Conclusions

This paper has described the main features and outputs of a model that has been developed to analyse the asset management and life cycle cost of the railway OLE system. A complete modelling framework has been developed, where, first of all, the user selects the inputs to the model, which are associated with the components studied and the asset management strategy considered. Then the Petri Net model is generated automatically and evaluated to obtain the output results, associated with the performance and cost of the components and the OLE system.

The proposed methodology is transferrable to other types of engineering systems that are subject to degradation, failure, inspection and maintenance processes. The set of outputs obtained allows decision makers to gain a better understanding of the expected performance and cost of the system over its entire life cycle under a given maintenance strategy. Such results can be used to predict future maintenance volumes, system reliability and the expenditure associated with the operation of the system. The outputs can be obtained for the different component types individually or for the overall system. Similarly, alternative maintenance strategies, which involve different start time, duration and type of maintenance, inspection and renewals can also be tested in the model. An example study analysis of a two-mile section of OLE demonstrated how the outputs can be used by decision makers to study the effects of asset management projects on system performance and its cost.

In terms of maintenance related outputs, the spikes in the number of maintenance visits to the access area coincides with the occurrence of high level intrusive inspections every four years. In terms of failure related outputs, events caused by external influences occur with a far greater rate than the failure of any of the OLE components; however, external failures are relatively simple to rectify, therefore the cost of such failures is low, in comparison to the OLE component failures. The failure cost of the contact wire is significantly higher than of any other OLE component; this is due to the fact there is an increased risk of extensive damage once the contact wire splits. In terms of life cycle cost, the mean failure cost is significantly greater than the mean maintenance cost, due to fines relating to the disruption to the timetabled service during a failure event. Finally, the mean total cumulative cost is approximately 20% larger if opportunistic maintenance is not used. Opportunistic maintenance results in fewer maintenance visits and the component maintenance actions are undertaken sooner, which also reduces the number of failures.

Future work involves developing an optimisation procedure which can be used in conjunction with the HLPN model to search for optimum maintenance strategies. For example, the type and frequency of inspection and maintenance actions that result in the lowest cost over the 100-year period can be found using an optimisation procedure.

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References

1. Network Rail. Electrical Power Asset Policy. Internal Network Rail documentation. 2012
2. International Standards Organisation. ISO 55000:2014 Asset management -- Overview, principles and terminology. 2014
3. Skinner M, Kirwan A, Williams J. Challenges of developing whole life cycle cost models for Network Rail's top 30 assets. In IET and IAM Asset Management Conference 2011, London. 2011
4. British Standards. BS 5760: Part 23, Guide to Life Cycle Costing. 1997
5. Woodward DG. Life cycle costing - theory, information acquisition and application. International Journal of Project Management 1997; 15(6): 335-344
6. Korpi E, Ala-Risku T. Life cycle costing: a review of published case studies. Managerial Auditing Journal 2008; 23(3): 240-261
7. Sherif YS, Kolarik WJ. Life cycle costing: concept and practice. Omega 1981; 9(3): 287-296
8. Frangopol DP, Dong Y, Sabatino S. Bridge life-cycle performance and cost: analysis, prediction, optimisation and decision-making. Structure and Infrastructrure Engineering, 2017; 13(10), 1239-1257
9. Swei O, Gregory J, Kirchain R. Probabilistic Characterization of Uncertain Inputs in the Life-Cycle Cost Analysis of Pavements. Transportation Research Record: Journal of the Transportation Research Board, No. 2366, 2013; 71–77
10. Lagaros ND, Karlaftis MG, Paida MK. Stochastic life-cycle cost analysis of wind parks. Reliability Engineering and System Safety, 2015; 144, 117-127
11. El-Din MN, Kim J. Simplified seismic life cycle cost estimation of a steel jacket offshore platform structure, Structure and Infrastructure Engineering, 2017; 13(8), 1027-1044
12. Jung P, Seo J, Lee J. Probabilistic value analysis methodology for public water supply systems, Civil Engineering and Environmental Systems, 2009; 26:2, 141-155

13. Ho TK, Chi YL, Ferreira L, Leung KK, Siu LK. Evaluation of maintenance schedules on railway traction power systems. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 2006; 220(2): 91-102
14. Chen SK, Ho TK, Mao BH. Reliability evaluations of railway power supplies by fault-tree analysis. IET Electric Power Applications 2007; 1(2): 161-172
15. Min LX, Yong WJ, Yuan Y, Yan XW. Multiobjective optimization of preventive maintenance schedule on traction power system in high-speed railway. In Reliability and Maintainability Symposium, 2009 (RAMS 2009), Fort Worth, IEEE, 365-370
16. Dutuit Y, Châtelet E, Signoret JP, Thomas P. Dependability modelling and evaluation by using stochastic Petri nets: application to two test cases. Reliability Engineering & System Safety 1997; 55(2): 117-124
17. Girault C, Valk R. Petri nets for systems engineering: a guide to modeling, verification, and applications. Berlin, Springer Berlin Heidelberg. 2003
18. Le B, Andrews JD. Modelling wind turbine degradation and maintenance. Wind Energy; 19(4): 571-591
19. Kilsby P, Remenyte-Prescott R, Andrews JD. A modelling approach for railway overhead line equipment asset management, Reliability Engineering and System Safety 2017; Special Issue on Maintenance Modelling, 168, 326-337
20. Kilsby P, 2017. Modelling Railway Overhead Line Equipment Asset Management. PhD Thesis, University of Nottingham
21. British Standards, 2010. BS ISO/IEC 15909-1:2004+A1:2010 Systems and software engineering- High-level Petri nets - Part 1: Concepts, definitions and graphical notation
22. Kiessling F, Puschmann R, Schmieder A, Schneider E, 2009. Contact Lines for Electric Railways. Erlangen, Publicis
23. Petri, C. A., 1962. Kommunikation mit automaten. PhD Thesis, University of Bonn

24. Network Rail, 2011. NR/L2/ELP/21087 Specification of maintenance frequency and defect prioritisation of 25kV overhead line electrification equipment. Internal NR documentation